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Special Section:
Magmatic and volcanic processes in continental rifts

Key Points:
- We document the initiation of a proto-transform fault during late-stage continental rifting in Afar, Ethiopia
- Surface faulting, seismicity, and geodetic observations reveal extensional transfer between magmatic segments
- Numerical modeling predicts that the region between the offset magmatic segments will evolve to a stable oceanic transform fault

Supporting Information:
- Supporting Information S1
- Data Set S1

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Initiation of a Proto-transform Fault Prior to Seafloor Spreading

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Abstract Transform faults are a fundamental tenet of plate tectonics, connecting offset extensional segments of mid-ocean ridges in ocean basins worldwide. The current consensus is that oceanic transform faults initiate after the onset of seafloor spreading. However, this inference has been difficult to test given the lack of direct observations of transform fault formation. Here we integrate evidence from surface faults, geodetic measurements, local seismicity, and numerical modeling of the subaerial Afar continental rift and show that a proto-transform fault is initiating during the final stages of continental breakup. This is the first direct observation of proto-transform fault initiation in a continental rift and sheds unprecedented light on their formation mechanisms. We demonstrate that they can initiate during late-stage continental rifting, earlier in the rifting cycle than previously thought. Future studies of volcanic rifted margins cannot assume that oceanic transform faults initiated after the onset of seafloor spreading.

1. Introduction

Transform faults have long been known to play a key role in seafloor spreading (Macdonald et al., 1988). They link and accommodate strike-slip motion between laterally offset mid-ocean ridge segments and occur in ocean basins worldwide. Despite the prevalence of oceanic transform faults, their initiation has not been directly observed, and thus, their formation mechanisms are poorly understood. Oceanic transform faults rely heavily on strain accommodation by magmatism and are orthogonal to spreading segments and parallel to the spreading direction (Taylor et al., 1995). In contrast, extension in early-stage continental rifts is controlled by slip on overlapping, en echelon normal faults (Ebinger, 1989). Where these faults overlap, they are linked by oblique accommodation zones (Bosworth et al., 1986; Ebinger, 1989). Previous numerical modeling of continental rifting has suggested that oceanic style transform faults do not form in early-stage rifts (Allken et al., 2012), so it is generally assumed that transform faults originate during seafloor spreading (Eagles et al., 2015; Nguyen et al., 2016). However, it is not known whether transform faults can initiate in mature continental rift systems.

The geometric correspondence between mid-ocean ridges and the segmentation of passive margins has led some studies to propose that some large-scale fracture zones have structural inheritance from the late stages of continental rifting (Behn & Lin, 2000; Cochran & Martinez, 1988; McClay & Khalil, 1998). In contrast, many studies suggest that short-scale transform faults are not inherited from continental rift geometry and the majority of transform faults show no clear evidence of structural inheritance (Bosworth et al., 1986; Taylor et al., 1995, 2009). The Danakil region, in northern Afar, Ethiopia/Eritrea, is one of the few areas on Earth where the final stages of continental rifting are subaerially exposed (Figure 1). The region thus provides a unique opportunity to explore the timing of transform fault initiation and to understand the kinematics of their formation.

1.1. Continental Rifting in Northern Afar

In Afar, the southern extent of the Red Sea rift steps on land into the Afar depression (McClusky et al., 2010; Figure 1). The crust thins from ~27 km in the central and southern Afar rift to <15 km beneath the Danakil region in the north (Hammond et al., 2011; Makris & Ginzburg, 1987). However, the crust in the Danakil region is

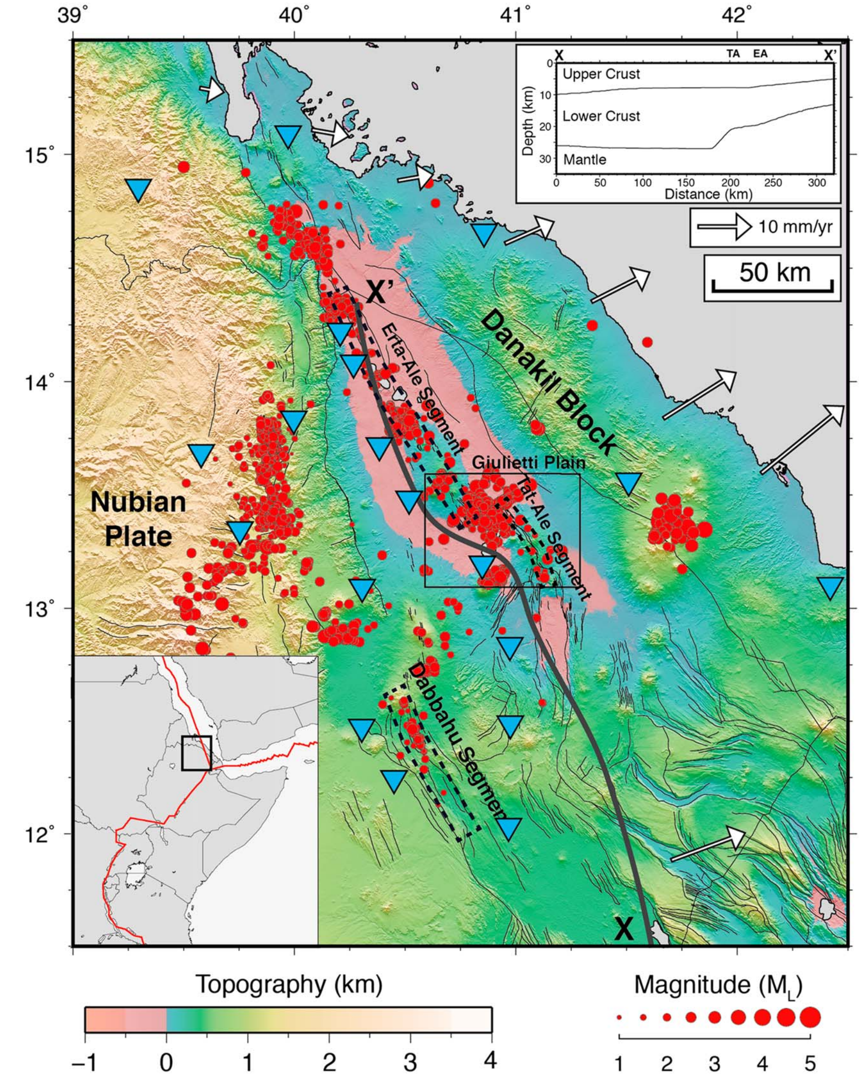

Figure 1. Main figure shows the location of the seismic network (blue inverted triangles) and all recorded earthquakes with horizontal errors <5 km (red circles) from 2011 to 2013 (Illsley-Kemp et al., 2018), superimposed on topography taken from the Shuttle Radar Topography Mission. A cluster of events is located in the Giulietti Plain, between the offset Erta-Ale and Tat-Ale segments. The box encloses the area shown in Figures 2–4. White arrows denote GPS velocities, relative to a stationary Nubian plate (McClusky et al., 2010). Surface faults shown in black taken from Manighetti et al. (2001) and Illsley-Kemp et al. (2017). Cross section X–X′ marks the seismic refraction profile of Makris and Ginzburg (1987), showing thinned crust (<20 km) beneath the Giulietti Plain. Inset shows the location of the Danakil region in East Africa.

still significantly thicker than that commonly observed in the oceans (White et al., 1992), which, together with its seismic velocity structure (Hammond et al., 2011; Makris & Ginzburg, 1987), suggests it is thinned and heavily intruded continental crust. The marked thinning of the crust into the Danakil region has been attributed to a late stage of plate weakening and stretching caused by protracted and localized magma intrusion (Bastow & Keir, 2011). Since the Quaternary, strain in Afar has localized to axial magmatic segments, hypothesized to be the future boundary of continental breakup (Hayward & Ebinger, 1996), and is thought to be accommodated through magmatic intrusions and associated mechanical faulting (Barberi & Varet, 1977; Manighetti et al., 2001; Wolfenden et al., 2005). Illsley-Kemp et al. (2018) have shown that the majority of seismicity and extension is focused at the rift axis, which steps en echelon to the northeast from the Dabbahu magmatic segment. However, a significant amount of seismicity occurs at the western rift margin, in a complex set of marginal grabens (Figure 1).

In the Danakil region, two currently active magmatic spreading segments, the Erta-Ale and Tat-Ale segments, separate the Nubian plate from the Danakil microplate (Figure 1). The Erta-Ale magmatic segment consists

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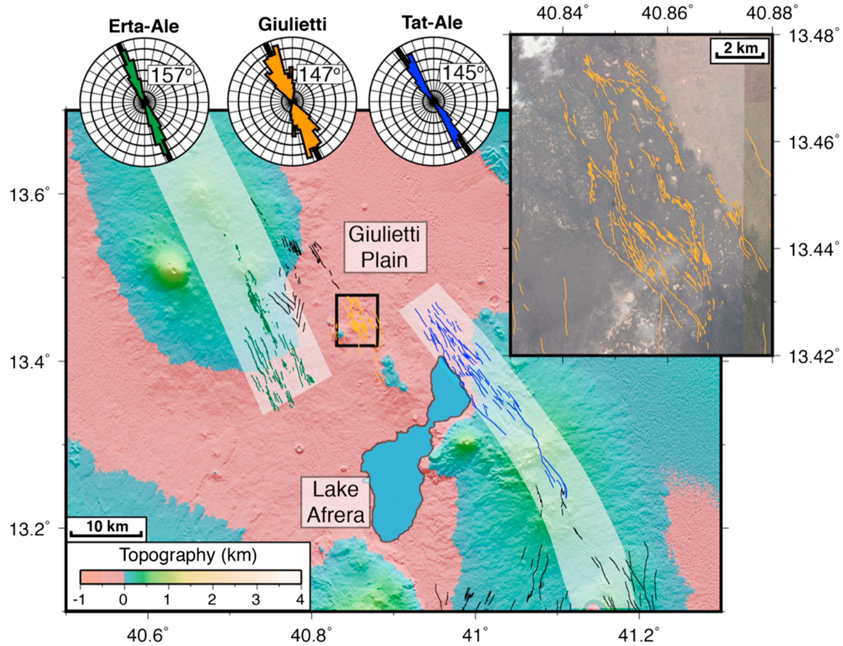

Figure 2. Surface faults and their associated rose diagrams show mean orientations that are consistent with regional extension in the Erta-Ale (green rose diagram) and Tat-Ale (blue rose diagram) segments. However, within the Giulietti Plain (orange rose diagram) surface faults display a greater variation, consistent with an interaction between the two spreading segments. Inset shows a zoom of the Giulietti Plain faults overlain on satellite imagery (Google Earth).

of 12 volcanic centers, including Erta-Ale volcano with its persistent lava lake (Keir et al., 2013). To the south, offset laterally by ~20 km to the east is the Tat-Ale magmatic center. The Giulietti Plain lies in the offset region between the Erta-Ale and Tat-Ale magmatic segments (Figure 2). The plain is below sea level and is predominantly overlain by evaporites from repeated marine incursions (Keir et al., 2013) and contains the saline Lake Afrera. Acoustic bathymetric profiles from the lake reveal Red Sea parallel normal faults intersected by oblique structures. These structures have been compared to those responsible for nodal deeps at oceanic transforms (Bonatti et al., 2017). Extension rates in the Danakil region are analogous to ultraslow/slow spreading ridges (Dick & Schouten, 2003) varying from ~7 mm/year in the north (15°N) to ~20 mm/year in the south (13°N). Extension is orientated 058°, roughly perpendicular to the spreading segment axes (McClusky et al., 2010).

2. Observational Methods and Results

2.1. Structural Geology

Surface faults were mapped remotely using Google Earth (DigitalGlobe) and ArcGIS. The surface expression of faults was mapped and digitized to create a detailed fault map (Figure 2). The strike of the faults was approximated using the start and end points of each mapped fault. Strike distributions are weighted according to fault length and displayed in 10° binned rose diagrams (Figure 2).

Analysis of the mapped surface faults (>2,000 faults) demonstrates that mean orientations within the Erta-Ale (157° ± 14°) and Tat-Ale (145° ± 8°) segments are consistent with the direction of maximum extension, which is approximately 058° (McClusky et al., 2010). In addition, these segments exhibit low variation in fault orientations, whereas surface faults in the Giulietti Plain show greater variability (147° ± 28°; Figure 2). While we must consider the possibility that not all of these surface faults are tectonic in origin (e.g., Eusden et al., 2005), we interpret the increased variability in fault orientations in the Giulietti Plain as being due to interaction between the Erta-Ale and Tat-Ale magmatic segments. The increased variability may also be evidence for an immature, evolving fault zone (e.g., Hatem et al., 2017).

2.2. Seismicity

A network of 20 seismometers in both Ethiopia and Eritrea (Figure 1) provided continuous seismic data for 2 years between February 2011 and February 2013. A total of 4,971 earthquakes of magnitude 0.4–5.8 was recorded during the experiment and was located with a 2-D velocity model (Hammond et al., 2011; Lomax

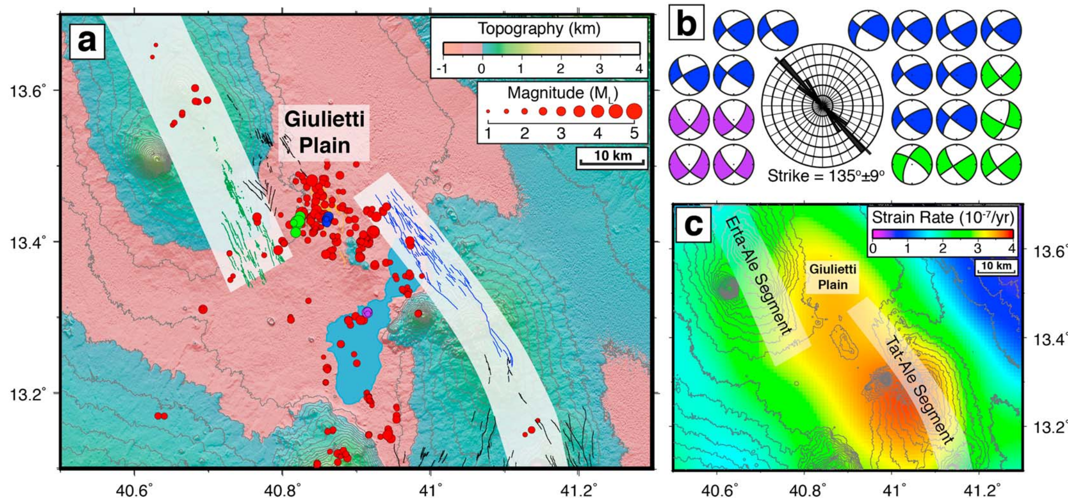

Figure 3. (a) Relocated earthquakes with average location error of ±0.55 km highlight a clear zone of deformation. (b) Focal mechanisms for three clusters (color coded in a) display characteristic right-lateral, oblique strike-slip motion. (c) Interferometric synthetic aperture radar and GPS derived maximum horizontal shear strain rate clearly showing a region of high strain rate within the Giulietti Plain. The combination of observations from the Giulietti Plain indicates that extension is transferred between the spreading segments through oblique shear.

et al., 2000; Makris & Ginzburg, 1987). These earthquakes have average location errors of ±1.9 km and ±4.1 km in the horizontal and vertical directions, respectively, and the catalogue is complete above magnitude 2.0 (Illsley-Kemp et al., 2017). Generally, earthquakes are focused at the western rift margin, which separates the Ethiopian plateau from the Afar depression, or in the vicinity of volcanic centers (Illsley-Kemp et al., 2018; Figure 1). In addition, there is a cluster of 418 earthquakes focused within the Giulietti Plain, (Figure 1).

We relocate the seismicity within the Giulietti Plain using GrowClust (Trugman & Shearer, 2017; Figure 3a), a technique that develops upon the double-difference relocation method (Waldhauser & Ellsworth, 2000). This process increases the relative location accuracy for clustered earthquakes. Initial average location errors were markedly improved for relocated events, which have an average relative hypocentral error of ±0.55 km. The majority of the relocated earthquakes occur in the upper 5 km of the crust. Focal mechanisms were calculated for three clusters of relocated earthquakes using the polarities of the first *P* and *S* wave arrivals and the software FocMec (Snoke, 2003). The resultant focal mechanisms display a characteristic right-lateral strike-slip motion with a component of extension (Figure 3b). The nodal plane is inferred from surface faults resulting in a mean strike and dip of 135° ± 9° and 75 ± 7°, respectively.

2.3. Satellite Geodesy

We combine an extensive set of interferometric synthetic aperture radar (InSAR) from multiple tracks and GPS measurements (Figure S1 in the supporting information) to invert for the three-dimensional velocity and strain field of Afar, following a two-step approach (Pagli et al., 2014). We obtained maps of the line-of-sight average surface velocities for each InSAR track using a multi-interferogram method (Wang & Wright, 2012), and then we combined these with the GPS velocities using a velocity field method (Kogan et al., 2012). The line-of-sight interferograms were created using images from the Envisat satellite in both descending and ascending orbits, in image and wide-swath modes, spanning the period between 2007 and 2010 (Pagli et al., 2014). GPS sites in central Afar were measured between 2007 and 2010 (Kogan et al., 2012), while GPS velocities from the Red Sea coast, the Gulf of Aden, and the Main Ethiopian rift are from other sources (Kogan et al., 2012; McClusky et al., 2010; Saria et al., 2014; Vigny et al., 2006, 2007). All GPS velocities were combined in the common International Terrestrial Reference Frame 2008 and given with respect to a stationary Nubian plate. Sudden deformations, induced by eruptions and dyke intrusions in Afar, were subtracted from the GPS as well as the InSAR data as they may affect the strain field in the Giulietti Plain (Pagli et al., 2014). No sudden deformations were removed from the Giulietti Plain; therefore, the strain field in our study area is complete.

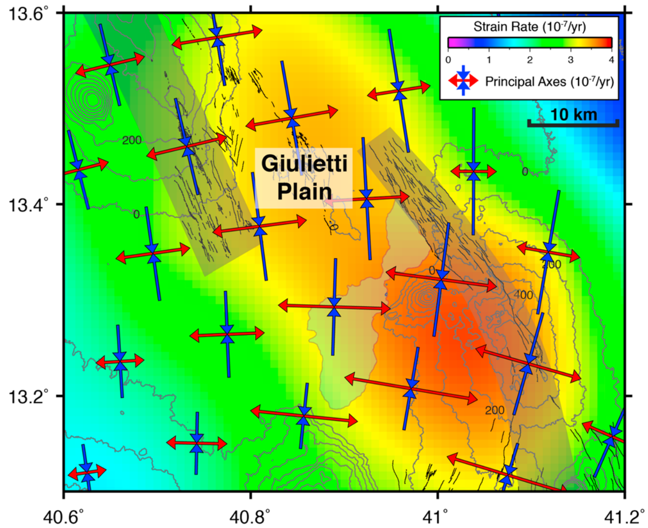

Figure 4. The principal axes of observed maximum horizontal shear strain rates in the Giulietti Plain, from interferometric synthetic aperture radar and GPS data. Extensional (red) and compressional (blue) principal axes of the strain rates, plotted on the maximum shear strain rate. Axes are consistent with right-lateral strike slip on NW-SE fault planes within the Giulietti plain, in agreement with observed seismicity (Figure 3).

To invert for the continuous three-dimensional velocity field, we divided the Afar region into a mesh of triangular elements (Figure S1) and assumed that the velocity varies linearly within each triangle (Pagli et al., 2014). The geodetic observations (InSAR and GPS) within each triangle are related to the velocities of their vertices by an interpolation function. We inverted for the velocities of the triangular vertices using the system of equations described by Nooner et al. (2009). The system was solved using a least squares method that included full variance-covariance matrices as well as smoothing with a Laplacian operator. A smoothing factor that minimizes the trade-off between the solution roughness and the weighted root-mean-square misfit of the model was selected (Pagli et al., 2014). After finding the velocities at the vertices of the triangles, we calculate the horizontal strain rates at each vertex using spherical approximation equations (Savage et al., 2001).

We find a region of elevated maximum horizontal shear strain rate (up to 4×10^{-7} year^{-1}) concentrated between the Tat-Ale and Erta-Ale segments, with the maximum shear strain rate to the west of the Tat-Ale segment (Figure 3c). No sudden discrete or large-magnitude deformation has occurred in the vicinity of the Giulietti Plain during this period, and therefore, we interpret the strain rates as representative of the tectonic regime. These geodetic results show that active shear is occurring in the Giulietti Plain.

2.4. Summary of Observations

The strike-slip events show excellent correlation with the observed region of maximum shear strain rate (Figure 3c). In addition, our focal mechanisms are consistent with the orientations of principal strain rate axes, which suggest right-lateral strike-slip faults on planes generally trending NW-SE (Figure 4). The surface faults in the Giuletti Plain have a range of orientations, from approximately NW-SE to approximately N-S (Figure 2); the strike of the focal mechanisms (135°) aligns with the most NW-SE of these surface faults. This suggests that the NW-SE oriented surface faults are active in the present day. Accordingly this suggests that the approximately N-S oriented surface faults were active in the past but are inactive now. Therefore, the orientation of faulting within the Giulietti Plain has rotated in an anticlockwise direction through time. The combination of earthquake locations, focal mechanisms, surface faulting trends, and geodetic strain rates implies that the right-lateral strike-slip events are accommodating oblique shear between the two magmatic segments. In this way, extension is transferred between the two magmatic segments.

3. Thermomechanical Numerical Modeling

The nucleation and evolution of oceanic transform faults has been the subject of several analogue and numerical modeling studies (Gerya, 2012, and references therein). Analogue freezing wax experiments (e.g., O'Bryan et al., 1975) reproduced features indicative of seafloor spreading, including transform faults and inactive fracture zones. These studies showed that the spreading parallel pattern of transform faults is an intrinsically preferential orientation. With the advent of high-powered computing, studies involving complex three-dimensional numerical models have begun to investigate transform fault formation. Such numerical studies (e.g., Choi et al., 2008; Gerya, 2013b; Hieronymus, 2004) suggest that crustal thinning is promoted in the region of the transform fault at low to intermediate spreading rates. In addition, these studies suggest that transform faults can form at initially straight ridges, which become unstable due to asymmetric crustal accretion. This leads to the formation of a new transform fault and suggests that they are not necessarily inherited from offsets in the initial rift (Gerya, 2010a, 2010b).

To investigate the temporal evolution of this extension transfer in the Giulietti Plain, we use high-resolution 3-D thermomechanical numerical models that simulate the extensional setting in the Danakil region. The Eulerian-Lagrangian viscoplastic model with an internal free surface allows for large strains and spontaneous crustal growth by magmatic accretion. The employed numerical technique (Gerya, 2010a, 2010b, 2013b) is based on a combination of a finite difference method applied on a uniformly spaced staggered finite

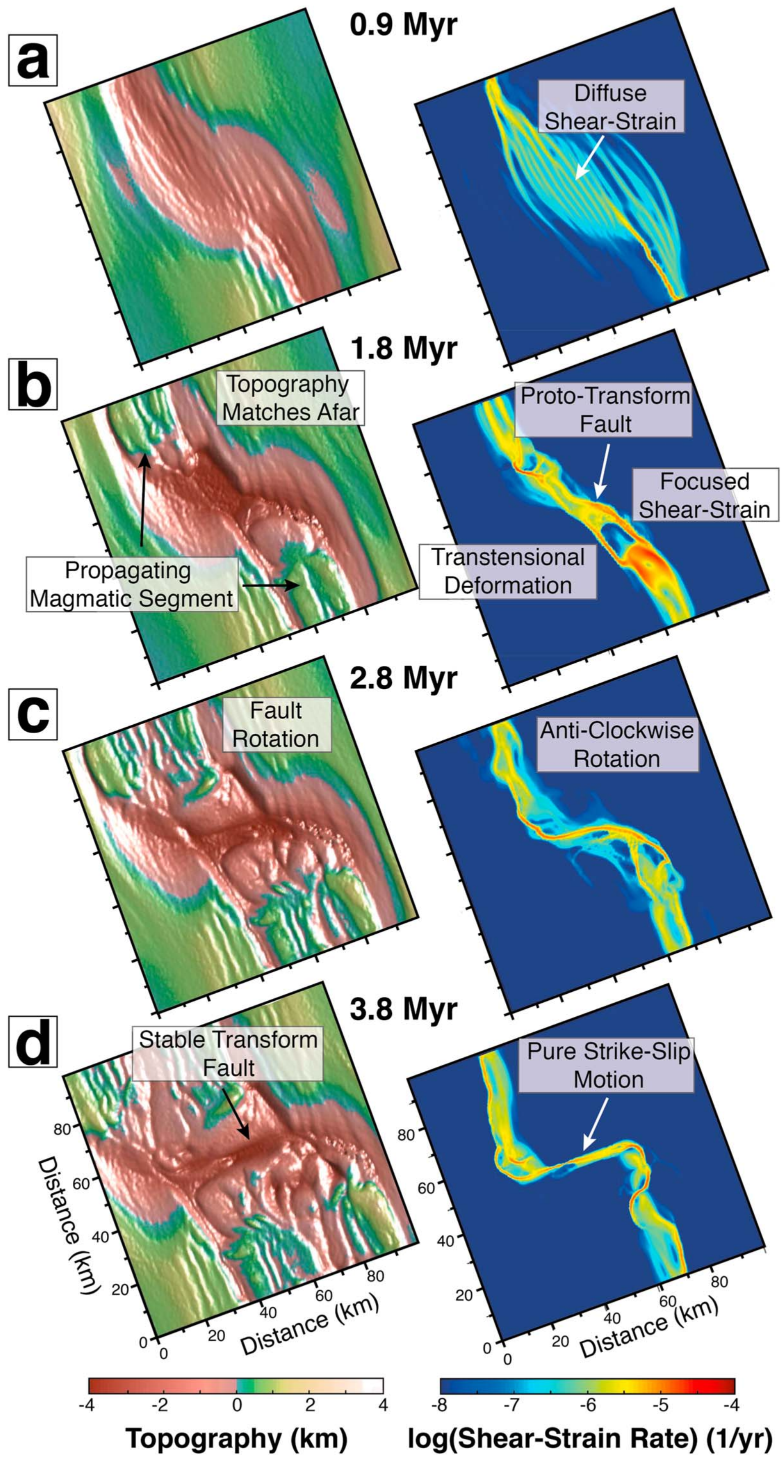

Figure 5. Time steps refer to time after model initiation. Topography (pink below sea level) and horizontal shear strain rate (at depth of 5 km) initially show a diffuse distribution of shear strain (a). This shear strain develops into a narrow region of transform oblique shear strain at ~1.8 Myr (b) and acts as a proto-transform fault. The topography and ~27° angle between proto-transform fault and volcanic segment closely resemble the topography and strike of earthquakes in Afar. In addition, the modeled horizontal shear strain is of a similar magnitude to that observed in the Giulietti Plain (Figure 3c). The model predicts that the proto-transform fault is transtensional, which would produce oblique strike-slip earthquakes, as seen in the Giulietti Plain. The proto-transform fault then rotates (c) toward a spreading parallel orientation; this would produce an anticlockwise rotation of surface faults as seen in the Giulietti Plain. At 3.8 Myr (d), the proto-transform fault becomes a stable, spreading parallel transform fault, which separates the two magmatic segments and is a persistent feature for the remaining model time.

difference grid, with the marker-in-cell technique. Full details of the numerical modeling are given in Gerya (2013b).

The initial model setup corresponds to late-stage continental rifting in northern Afar, with a 20-km-thick crust (Figure S3). Similarly to previous numerical models of spontaneous plate fragmentation (Choi et al., 2008; Gerya, 2013b; Hieronymus, 2004), two linear thermal perturbations (weak seeds) with an offset of 20–40 km are imposed at the bottom of the lithospheric mantle. The modeled (full) spreading rate corresponds to 20 mm/year, taken from GPS studies in the region (McClusky et al., 2010). The numerical model thus simulates the final stages of continental rifting, where the crust has been significantly modified by repeated magmatic intrusions, such as in Afar.

The momentum, mass, and heat conservation equations are solved with the thermomechanical code I3ELVIS (Gerya & Yuen, 2007) on the nondeforming Eulerian grid, whereas the advection of transport properties including viscosity, plastic strain, temperature, etc. is performed by advecting the Lagrangian markers. We adopted the tectonomagmatic numerical model of rifting and spreading developed by Gerya (2013b), which accounts for the four key physical processes: (i) thermal accretion of the oceanic mantle lithosphere resulting in plate thickness growth, (ii) partial melting of the asthenospheric mantle, melt extraction, and percolation toward the ridge resulting in crustal growth, (iii) magmatic accretion of the new crust under the ridge, and (iv) hydrothermal circulation at the axis of the ridge, resulting in excess cooling of the crust. These physical processes are included in our numerical model in a simplified manner.

Thermal accretion of the mantle lithosphere is modeled by solving the heat conduction equation combined with a temperature-dependent viscosity for the nonmolten mantle (Katz et al., 2003). Consequently, cooling causes asthenospheric mantle to become rheologically strong and accrete spontaneously to the bottom of the lithosphere. Hydrothermal circulation at the axis of the ridge, producing rapid cooling of the new crust (Theissen-Krah et al., 2011), is parameterized with an enhanced thermal conductivity of the crust in the regions located below sea level (Gregg et al., 2009). The hydrothermal circulation in the crust is controlled by the Nusselt number, which we range between 1 and 2 (Gerya, 2013b) and find that it has little effect on model evolution. Partial melting of the asthenospheric mantle, melt extraction, and percolation toward the ridge is implemented in a simplified manner. According to our model, crustal growth at the ridge is balanced by the melt production and extraction in the mantle. However, melt percolation toward the ridge (e.g., Katz, 2010) is not modeled directly and considered to be nearly instantaneous (Connolly et al., 2009). Lagrangian markers track the amount of melt extracted during the evolution of each experiment. Magmatic accretion of the new crust is modeled by spontaneous cooling and crystallization of melts at the walls of the lower-crustal magma regions (Wanless & Shaw, 2012).

The rheological response to elastic strain in the mantle and crust is controlled by the upper strain limit for fracture-related weakening (γ_0). The Eulerian computational domain is equivalent to 98 × 98 × 50 km and is resolved with a regular rectangular grid of 197×197×101 nodes and contains 34 million randomly distributed Lagrangian markers. We performed 16 numerical experiments (Table S1) by systematically varying different model parameters in their uncertainty ranges. Here we describe the evolution of the reference model *afab*.

3.1. Modeling Results

During the initial stages of the model, offset rift grabens form above the thermal perturbations (Figure 6a). At 0.9 Myr into the model, two volcanic ridges form at the center of the two grabens as a result of decompression melting of the rising asthenosphere. At this stage of the model new oceanic style crust begins to form at the volcanic centers through the crystallization of melt at the walls of the magmatic regions (Figure 6). The model does not attempt to simulate small-scale intrusions; thus, this formation of oceanic style crust may be analogous to the intrusion of dykes and sills, commonly observed in the Danakil region. Initially, these volcanic ridges are separated by ∼80 km in the along-strike direction. As the model develops the ridges propagate toward each other such that by 1.8 Myr they are separated along strike by ∼40 km and laterally by ∼20 km (Figure 5b), broadly the same configuration as the Erta-Ale and Tat-Ale segments in the Danakil region (Figure 3a). At this stage the volcanic centers begin to interact and form a narrow region of maximum horizontal shear strain that is orientated ∼27° to the trend of the volcanic ridges and has shear strain rates of ∼ 10^{-6}–10^{-5} per year, which is of a similar magnitude to the observed maximum horizontal shear strain (Figure 3c). This stage of the model can be considered to represent the emergence of a proto-transform fault

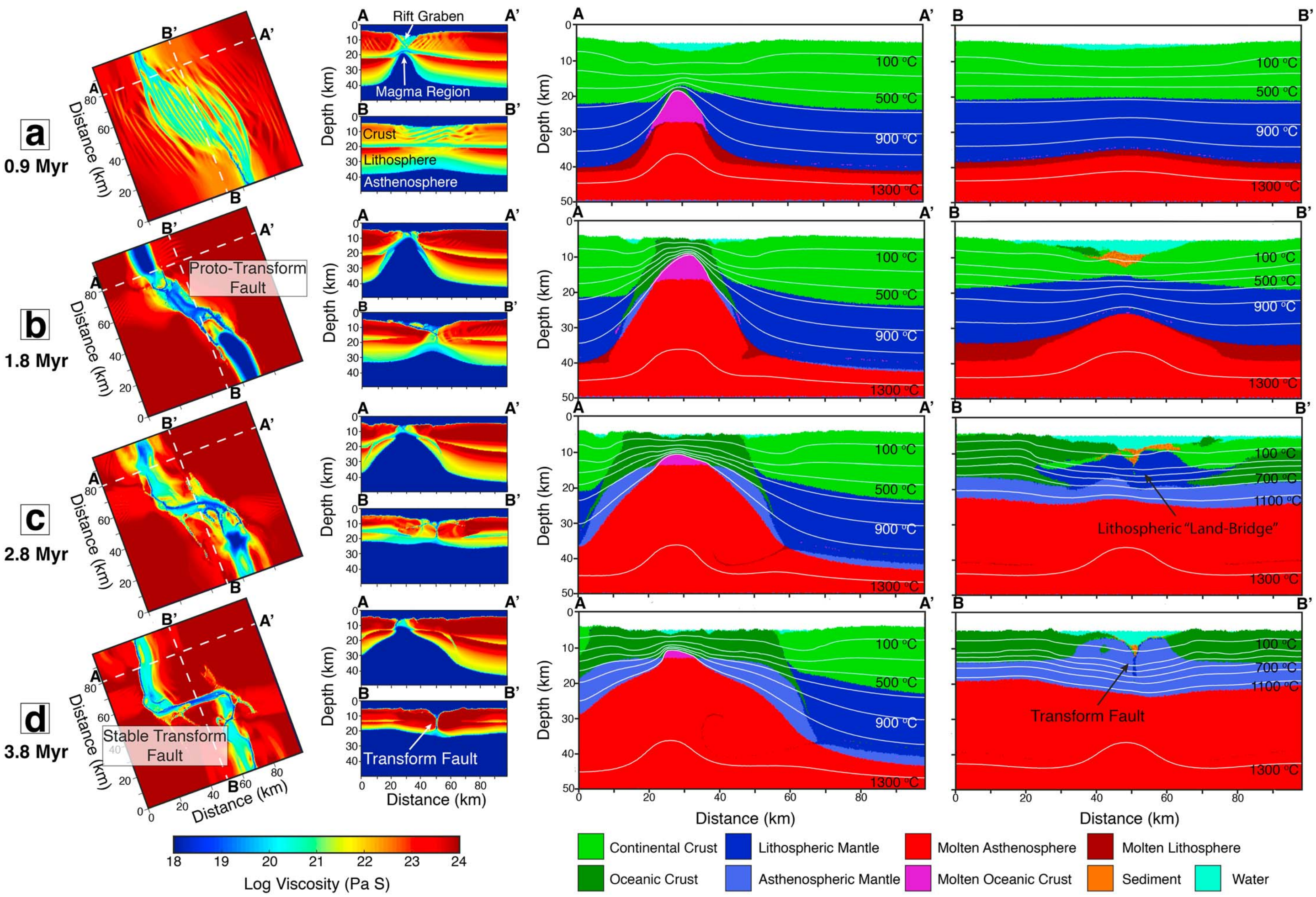

Figure 6. Viscosity variation and pseudogeological cross sections within the numerical model of the Giulietti Plain, northern Afar. Time steps refer to time after model initiation. The viscosity plots clearly show an evolution from broadly distributed deformation in (a) followed by the development of the proto-transform fault (b). The proto-transform fault rotates anticlockwise (c) and subsequently evolves to a stable, spreading parallel transform fault (d). Pseudogeological cross sections show the thinning of the continental crust and accretion of new crustal material. Continental lithosphere is present in the model up until 3.8 Myr, after the formation of a stable transform fault.

(Figure 5b). The angle of the proto-transform fault with respect to the volcanic ridges closely matches the angle between the average strike of earthquakes within the Giulietti Plain and the Erta-Ale segment (Figure 3b).

The model predicts that the deformation within the proto-transform fault is transtensional. This deformation would manifest itself as oblique strike-slip earthquakes in the upper crust, as is observed in the Giulietti Plain (Figure 3b). The extensional component of the proto-transform fault promotes opening and volcanism at the end of each volcanic segment, causing the segments to propagate toward each other (Figure 5). The proto-transform fault continually reconnects to the propagating segment tips, such that it undergoes an anticlockwise rotation toward a spreading parallel orientation (Figure 5c). Evidence for this anticlockwise rotation of deformation is shown in the surface faults of the Giulietti Plain (Figure 2).

As the model further develops (~2.8 Myr), the lithosphere in the proto-transform fault region is predicted to remain continental in composition and acts as a "bridge" maintaining a connection between the two plates (Figure 6c). The model then predicts that at ~3.8 Myr a transform fault will form between the volcanic segments (Figures 5d). At this stage deformation on the transform fault is purely strike slip. These transform faults are then stable features that are persistent in the model as it develops into a mature ridge-transform pattern, which closely resembles young, seafloor spreading segments (Taylor et al., 1995). Therefore, our results also suggest that once transform faults have initiated they are stable, persistent features that focus deformation

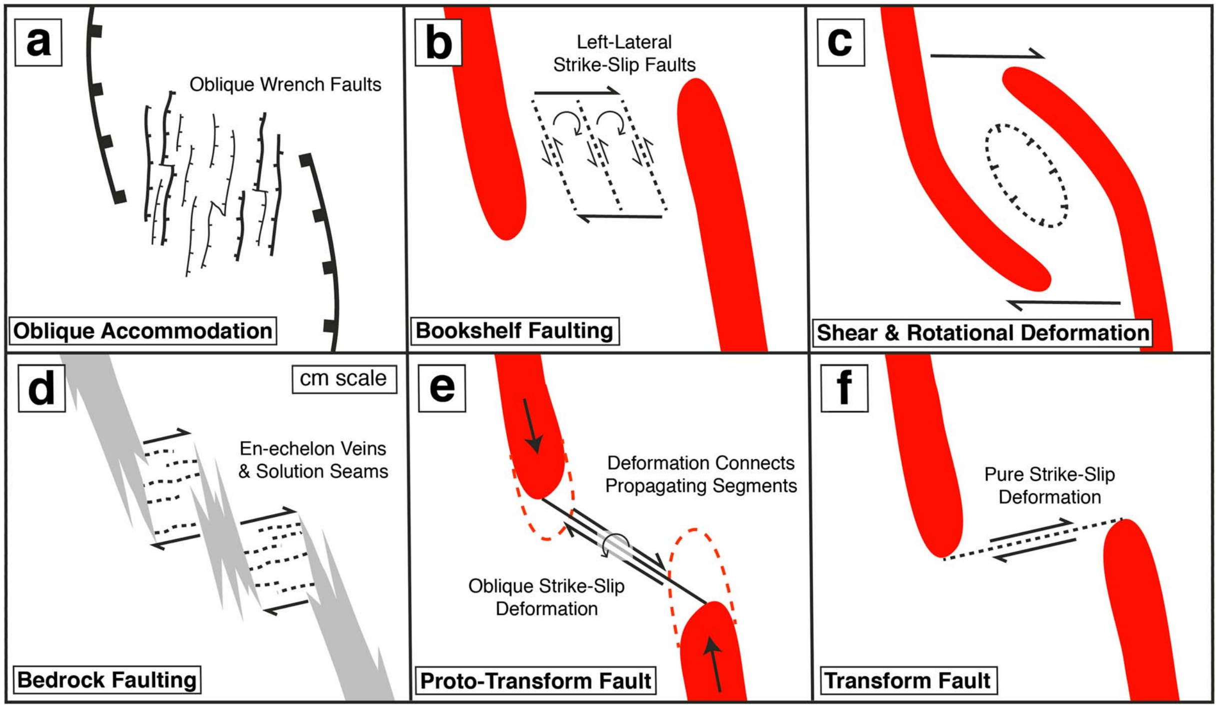

Figure 7. (a) Extensional transfer observed in early-stage continental rifting. Extension is focused along half-graben structures and transferred through a region of complex, oblique faults (Bosworth et al., 1986; Corti, 2008; Ebinger, 1989; Rosendahl, 1987). (b) Bookshelf faulting accommodates transfer of extension between overlapping oceanic spreading segments (Green et al., 2014). (c) Extension is transferred between overlapping spreading centers through a region of rotational deformation (Macdonald & Fox, 1983; Tyler et al., 2007). (d) Centimeter-scale faulting observed in bedrock that accommodates extensional transfer between microcracks (Willemse et al., 1997). (e) Extensional transfer through a proto-transform fault, observed in young seafloor spreading segments (Taylor et al., 2009) and proposed here for northern Afar. The proto-transform fault links propagating magmatic segments and rotates anticlockwise as the segments propagate. (f) Ridge-perpendicular, spreading parallel oceanic transform faults, which are characteristic of ocean ridges (Macdonald et al., 1988).

during the transition from continental rifting to seafloor spreading and that they will continue through to the mature oceanic ridge stage of plate tectonics.

4. Discussion

The mode of extensional transfer in the Giulietti Plain is not observed in early-stage continental rifts. In these less developed rifts, extension is focused along asymmetric half-graben structures and transferred through complex, oblique accommodation zones (Bosworth et al., 1986; Corti, 2008; Ebinger, 1989; Rosendahl, 1987; Figure 7a). These regions are extremely structurally complex and are dominated by oblique-slip normal faults, which strike subparallel to the rift (Bosworth et al., 1986). In analogue models of oblique rifting in the Main Ethiopian rift (Agostini et al., 2009; Corti, 2008; Corti et al., 2013), offset rift segments are connected by a region of strike-slip deformation very similar to what we observe in northern Afar. Conversely, these models predict that the accommodation zone will rotate in line with the sense of strike-slip motion. However, they do not account for the segment propagation, which is shown to play a key role in the rotation of the proto-transform fault toward a spreading parallel orientation (Figure 7e). It may be that the regions of strike-slip deformation observed in the Main Ethiopian Rift are precursors to proto-transform fault initiation.

Where ocean ridge segments overlap by several kilometers, a variety of mechanisms for the transfer of extension have been observed. In Iceland, shear motion between overlapping magmatic segments is shown to occur through bookshelf faulting. Green et al. (2014) detail how a region of focused seismicity between the Askja and Kverkfjöll segments is accommodating right-lateral shear motion. This occurs through strike-slip motion along a system of left-lateral faults, which are subparallel to the magmatic segments (Figure 7b). The bookshelf faulting mode of extensional transfer is therefore fundamentally different to observations from the Giulietti plain as the orientation of slip is opposite, and the active faulting in the Giulietti plain is oblique to the magmatic segments (Figure 3).

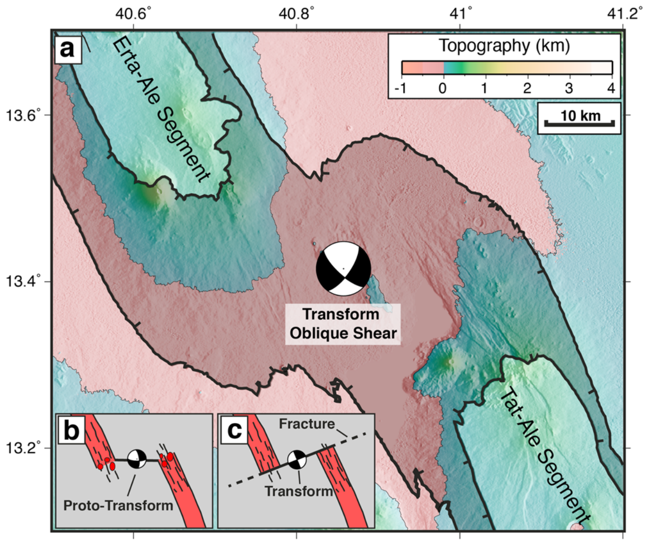

Figure 8. (a) Topography taken from the numerical model at 1.8 Myr (shaded below sea level, light above sea level) overlain on topography from the Giulietti Plain (pink below sea level) shows good agreement in the location of topographic highs and lows. The oblique, strike-slip faults that are observed in the Giulietti Plain are caused by the transtensional proto-transform fault, as predicted by the numerical model. Modeling further predicts that the proto-transform fault will rotate in an anticlockwise sense as volcanic segments propagate toward each other (b). The anticlockwise rotation of the proto-transform fault results in the observed rotation of surface faulting in the Giulietti Plain. The proto-transform fault then develops into a spreading parallel transform fault (c), with pure strike-slip motion. This is then a stable and persistent feature such as transform faults observed at mid-ocean ridges worldwide.

Another style of nontransform ocean ridge discontinuity is found where magmatic segments overlap by tens of kilometers. This results in a focused region of rotational deformation, which results in a volcanically active, elevated terrain (Macdonald & Fox, 1983; Tyler et al., 2007; Figure 7c). This central domain is the focus for shear and rotational deformation and is thought to be unstable with time. Macdonald and Fox (1983) use analogue models of spreading processes to suggest that the overlapping spreading segments will link, leading to the abandonment of the deformation zone. In contrast to previous examples, ocean ridge segments are often arranged en echelon, with characteristic, ridge-perpendicular oceanic transform faults (Behn & Lin, 2000; Figure 7f). A mode of extension transfer that is analogous to that currently observed in the Danakil region, and oceanic transform faults, is seen in small-scale faults in bedrock (Willemse et al., 1997; Figure 7d). In this setting, shear zones form en echelon veins, which are connected by a system of perpendicular to oblique solution seams. Extensional strain is transferred between veins through displacement along these solution seams.

Similar proto-transform fault systems (Figure 7e) have been observed in young seafloor spreading segments in the Woodlark Basin, Papua New Guinea (Taylor et al., 1995). These systems have been postulated to mark the initiation of transform faults yet are observed only in regions of young seafloor spreading. In addition, a similar mechanism of interacting, propagating magmatic rifts has been proposed for the formation of hyperextended margins such as those observed in the South Atlantic (Le Pourhiet et al., 2017). The Danakil region is therefore the first observed example of extension transferring between axial magmatic segments through a region of oblique shear, prior to the initiation of seafloor spreading.

Previous studies on transform fault formation do not consider axial localization of strain during continental breakup. However, observations and models of continental rifts increasingly show that as extension increases, faulting and magmatism become focused in rift to a narrow swath of dense faulting, volcanic centers, and aligned cones with subsurface dykes (Buck, 2006; Hayward & Ebinger, 1996; Kendall et al., 2005; Manighetti et al., 2001). The border faults that controlled the architecture of the young rift become less active as extension is focused at the rift axis (Ebinger & Casey, 2001; Hayward & Ebinger, 1996; Wolfenden et al., 2005). In terms of deformation mechanisms this mode of continental rifting is more closely analogous to seafloor spreading than early-stage continental rifting. In addition, the mechanisms of magmatic crustal accretion that have been observed at mid-ocean ridges (e.g., Carbotte et al., 2013) have initiated in the Danakil region (Illsley-Kemp et al., 2018). Thus, the transition from late-stage continental rifting to seafloor spreading must be considered as a prolonged process, and processes, which are considered indicative of seafloor spreading, can initiate prior to final continental breakup.

Considering that the observations from the Danakil region cannot be explained by any previously proposed modes of extensional transfer, the close correspondence between the numerical model and observations provides compelling evidence that the Giulietti Plain is at the proto-transform fault stage of formation. Our results therefore document the direct observation of proto-transform initiation and corroborate previously proposed mechanisms of formation (Gerya, 2013b). The development of the numerical model toward a stable oceanic style transform fault lends support to the interpretation that the Giulietti Plain is a proto-transform fault. However, we cannot preclude that the Giulietti Plain may develop into a throughgoing, continuous magmatic segment with a zero-offset transform (e.g., Schouten & White, 1980) and this behavior is predicted by model runs with elevated mantle temperatures (Table S1). The transfer of extension between magmatic segments through transform faults is a fundamental characteristic of seafloor spreading (Atwater & Menard, 1970; Macdonald et al., 1988). Our results demonstrate that proto-transform faults can initiate during late-stage continental rifting, prior to seafloor spreading (Figure 8). This provides further evidence that seafloor spreading processes can initiate earlier in the rifting cycle than previously thought. During our study period (2011–2013), deformation was focused at the Giulietti Plain; however, it is not clear whether this is a long-term pattern. There are many offset magmatic segments in Afar, and it is not clear whether the proto-transform process is limited to the Giulietti Plain. This study focuses on the Giulietti Plain as that is the only segment offset with measurable seismic and geodetic deformation. The lack of measurable deformation between other segment offsets strongly suggests that deformation related to rift linkage is episodic. Other regions of segment offset may have been active in the past and may become active in the future. For example, Pagli et al. (2014) suggest that the rift axis steps from the Tat-Ale segment to the Dabbahu segment in the SW (Figure 1). The sporadic seismicity in this region may be associated with this transfer of extension; however, significant deformation was not observed in this region during our study period.

Rifting in Afar occurs above anomalously hot mantle, which causes significant magma intrusion (Ferguson et al., 2013; Gallacher et al., 2016). This magmatism may enable the style of extension in Afar to be more similar to that observed at oceanic ridges (Illsley-Kemp et al., 2018; Keir et al., 2013). Studies of the magmatically less active Woodlark basin, Papua New Guinea, which exhibits the transition from continental rift to seafloor spreading, suggest that transform faults initiate as, or after, spreading nucleates (Gerya, 2013a). It is therefore not clear whether our interpretations regarding the timing of transform fault initiation apply beyond the formation of a volcanic rifted margin. However, our research suggests that future work on volcanic rifted margins should not assume that transform faults initiated after the onset of seafloor spreading.

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